FREQUENCY-SHIFT KEYING BY THE OUTPHASING METHOD

J. T. BURRILL

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FREQUENCY-SHIFT KEYING
BY THE OUTPHASING METHOD

J. T. BURRILL

FREQUENCY-SHIFT KEYING
BY THE OUTPHASING METHOD

by

J. T. BURRILL
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
in
ENGINEERING ELECTRONICS

UNITED STATES NAVAL POSTGRADUATE SCHOOL
Monterey, California
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PREFACE

This investigation of the feasibility of employing the outphasing method of single-sideband production for frequency-shift keying was undertaken at the United States Naval Postgraduate School in Monterey, California, during the academic year 1953-1954. The system has the primary advantage of permitting an effective frequency shift to be made at the desired channel frequency or submultiple, as well as employing amplitide-modulation and simple conventional circuitry. An experimental model was constructed to demonstrate the principles and difficulties involved.

Of great assistance in the preparation of this paper has been Professor Earl G. Goddard, to whom the writer is indebted for the suggestion of topic and guidance throughout the investigation.

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CHAPTER I

INTRODUCTION

1. Summary.

The method of production of single-sideband transmission by the outphasing technique may be employed for frequency-shift keying, wherein the upper and lower sideband signals are alternately transmitted in correspondence with the mark and space conditions of a teletypewriter input by phasing out the unwanted sideband. Signaling is accomplished by shifting a constant amplitude carrier between two frequencies, in effect, as in other keyers, but the production of each frequency is by means of an amplitude-modulation process rather than by means of frequency-modulation as in the common types of keyers.

An attractive feature of this system is the relative ease with which the "shifting" may be performed directly at the desired channel frequency or a submultiple thereof. Satisfactory frequency-shift systems are now in use, but the more common type employs a separate oscillator of a relatively low frequency as the source whose frequency is directly shifted. This oscillator output is then combined with the transmitter's frequency. In this way, the transmitter frequency must be offset from the desired channel frequency by an amount that bears an integral relationship with the keyer frequency. Other systems have been employed using the transmitter carrier frequency directly, and even in some cases two independent sources at the required separation. These latter systems have not proved very useful, and the offset frequency system involves a great probability of operator error in adjustment and operation as well as considerable bulk.

It is thus the objective of this paper to present the results of investigation and evaluation of the outphasing method of frequency-shift keying, particularly as it may be used to directly shift the transmitter frequency at the desired channel frequency or a direct submultiple thereof, and with the possibility of reducing the size and complexity of present keyers. This preliminary investigation was partially experimental and largely theoretical, and bears out the advantages and the limitations of the system.

2. Description of Basic System.

In the outphasing system, an r.f. excitation source, which is at the operating frequency or submultiple, is used as the carrier input to two balanced modulators, while an audio oscillator provides the modulating signal. The frequency of the audio signal is that of the desired shift above or below the mean frequency, taking into account that this may need to be a submultiple because of later frequency multiplications in succeeding stages of the transmitter. The r.f. carrier is split into two components that are identical except for a phase difference of 90 degrees. The audio signal is likewise split into two components of equal amplitudes, one having a phase difference of plus 90 degrees or minus 90 degrees with respect to the other. One r.f. and one audio component are combined in each of the balanced modulators. Each balanced modulator may be made up of two modulator tubes in control-grid, screen-grid or plate modulation, or of rectifiers (germanium, copper oxide, or thermionic) in bridge or ring modulator circuits.

In each balanced modulator the carrier and audio signals are supplied in such a way that the carrier does not appear in the output, or is greatly

suppressed, but that the sidebands do appear. The r.f. is introduced in parallel, for example, while the audio is introduced in push-pull. By taking the double-sideband output of each modulator in a pair to opposite ends of the output tuning coil (push-pull), the carrier component is balanced out or greatly suppressed, while both the sidebands remain. Balanced modulators can also be connected with the r.f. drive and the audio inputs in push-pull and the output in parallel with equal effectiveness.

One sideband is produced when the audio frequency components to the two balanced modulators bear a plus 90 degrees phase relationship, while the other sideband is produced when one of these components has been further shifted by 180 degrees. The possibility of shifting the phase of this one audio frequency component at a high rate of speed is the principal factor which makes this system suitable for teletypewriter operation, provided that in so doing only negligible distortion results.

One method is to make outputs of the audio signal 180 degrees in phase always available, say on opposite ends of an output coil or as the two outputs of a paraphase amplifier. Then a switching device is used to permit the selection of the proper audio phase at a high rate of speed and minimum transient time. The switching device must offer no change of the output phase in itself. It may perform the switch instantaneously without passing through intermediate phases, or it may do it by a fast, smooth transition passing through all intermediate phases. Additionally, when the audio modulation is removed from one pair of modulators, as during the mark-to-space transition, it is desirable to remove the audio modulation from the other pair to prevent the radiation of a double sideband signal.

The essential components of an experimental system constructed are shown

in the block diagram of Figure 1. With the keyer in one position, the upper sideband is phased out, and the lower sideband remains. With the keyer in the other position, the upper sideband remains. In a neutral condition of the keyer no output is produced, since the carrier is balanced out in the balanced modulators.

[illegible]. Mathematical Derivation of Outputs.

In the following treatment, the convention is followed of a voltage of 0 degrees phase being taken mathematically as a positive sine function. Vectorially, zero phase is taken as horizontally to the right with increasing phase counter-clockwise. A modulated wave, consisting of a carrier and both sidebands, is shown with the positive upper sideband vector arbitrarily at plus 30 degrees with respect to the position of a carrier vector of the same trigonometric form. Similarly, the positive lower sideband vector occupies the position of minus 30 degrees with respect to the position of a carrier vector of the same trigonometric form.

The following is a mathematical derivation of the single-sideband outputs. In producing the lower sideband, the key position is to the right, introducing the audio signal at 0 degrees phase to the phaseshift network. Modulator 1A in itself then produces the following double sideband signal:

$$-E(1+m\cos\omega_s t)\cos\omega_c t$$

$$= -E\cos\omega_c t - \frac{Em}{2}\cos(\omega_c+\omega_s)t - \frac{Em}{2}\cos(\omega_c-\omega_s)t$$

Modulator 1B produces the following:

$$-E(1-m\cos\omega_s t)\cos\omega_c t$$

$$= -E\cos\omega_c t + \frac{Em}{2}\cos(\omega_c+\omega_s)t + \frac{Em}{2}\cos(\omega_c-\omega_s)t$$

BLOCK DIAGRAM

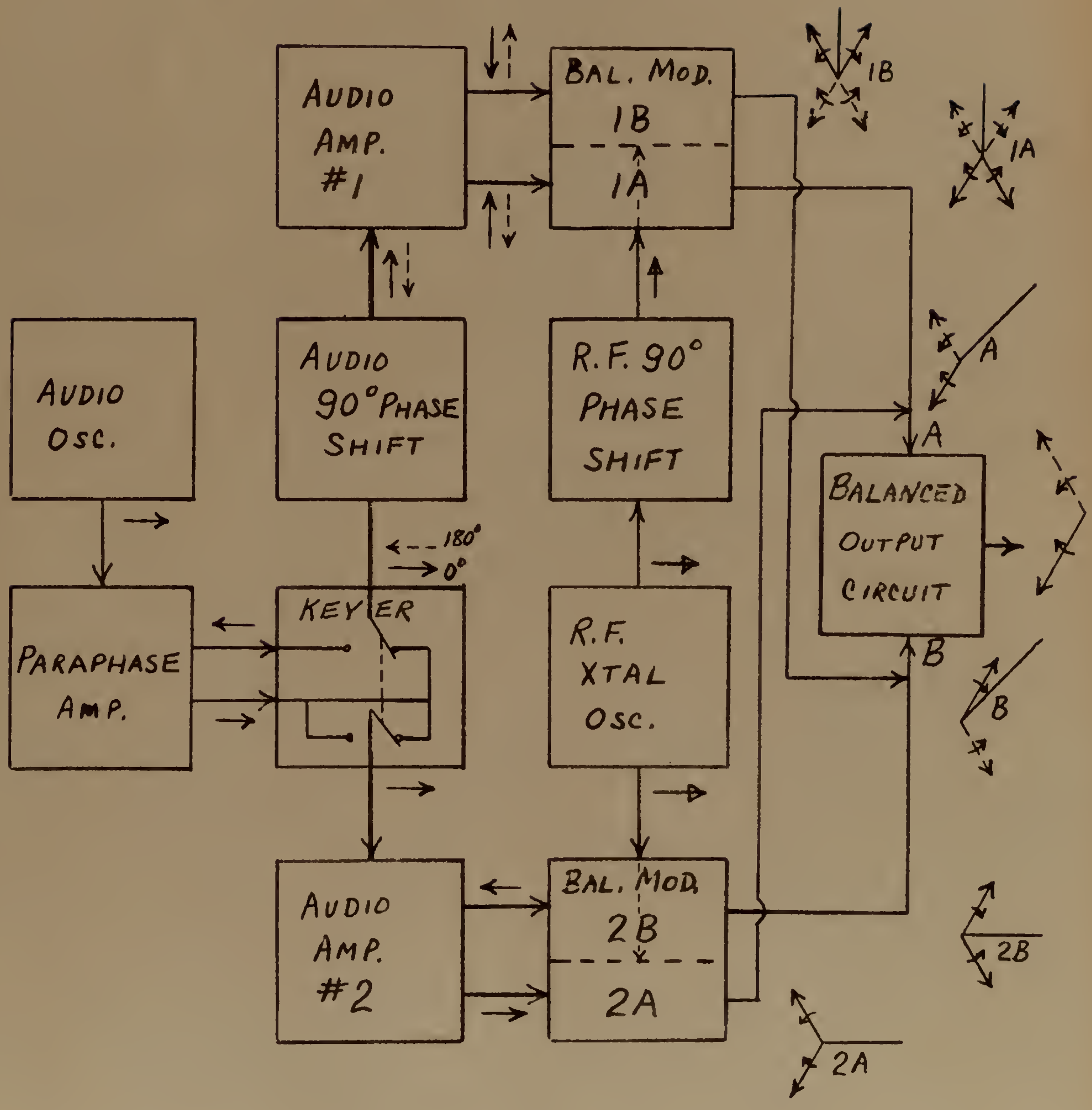

Fig. 1

Modulator 2A produces the following:

$$-E(1+m\sin\omega_s t)\sin\omega_c t$$

$$=-E\sin\omega_c t+\frac{Em}{2}\cos(\omega_c+\omega_s)t-\frac{Em}{2}\cos(\omega_c-\omega_s)t$$

Modulator 2B produces:

$$-E(1-m\sin\omega_s t)\sin\cdot\omega_c t$$

$$=-E\sin\omega_c t-\frac{Em}{2}\cos(\omega_c+\omega_s)t+\frac{Em}{2}\cos(\omega_c-\omega_s)t$$

The combination of 1A and 2A at point A of the output tuned circuit gives:

$$(1A+2A)$$

$$=-E(\cos\omega_c t+\sin\omega_c t)-Em\cos(\omega_c-\omega_s)t$$

The combination of 1B and 2B at point B of the output tuned circuit gives:

$$(1B+2B)$$

$$=-E(\cos\omega_c t+\sin\omega_c t)+Em\cos(\omega_c-\omega_s)t$$

Since points A and B are on opposite ends of the output coil, the net output becomes the difference:

$$A-B=-2Em\cos(\omega_c-\omega_s)t$$

which is the lower sideband.

In producing the upper sideband, the individual outputs of modulators 1A and 1B are changed, while that of 2A and 2B remain as before. Modulator 1A output becomes:

$$-E(1 - m\cos\omega_s t)\cos\omega_c t$$

$$= -E\cos\omega_c t + \frac{Em}{2}\cos(\omega_c+\omega_s)t + \frac{Em}{2}\cos(\omega_c-\omega_s)t$$

Modulator 1B output becomes:

$$-E(1 + m\cos\omega_s t)\cos\omega_c t$$

$$= -E\cos\omega_c t - \frac{Em}{2}\cos(\omega_c+\omega_s)t - \frac{Em}{2}\cos(\omega_c-\omega_s)t$$

so that at point A, (A = 1A + 2A)

$$= -E(\cos\omega_c t + \sin\omega_c t) + Em\cos(\omega_c+\omega_s)t$$

and at point B, (B = 1B + 2B)

$$= -E(\cos\omega_c t + \sin\omega_c t) - Em\cos(\omega_c+\omega_s)t$$

The net output then becomes:

$$A - B = 2Em\cos(\omega_c+\omega_s)t$$

which is the upper sideband.

It can easily be shown that if the audio signal had been reversed in phase to both pairs of modulators, no change in sideband would have been produced upon keying.

The vectorial combinations at the various output points are also shown on Figure 1, with the solid vectors representing the lower sideband and the dotted vectors representing the upper sideband.

CHAPTER II

COMPARISON WITH OTHER FREQUENCY-SHIFT SYSTEMS

1. General Types.

The generation of a frequency-shift keyed signal suitable for teletypewriter use may be accomplished in several ways. In general, these are of three types: shifting between two independent sources; variation of the basic frequency by a frequency-modulation process; and the use of an audio signal to modulate a carrier, producing a double-sideband of amplitude-modulation, from which the upper and lower sidebands are alternately selected.

Some success has been reported by Buff (1)* for ordinary telegraph frequency shift by using two crystals differing slightly in frequency and alternately keyed by means of an electronic switch or mechanical relay. Davey and Matte (2) mention that frequency shift keying has been provided by switching between two independent sources of carrier current separated by the desired shift, but point out that the frequency transitions often involve sudden phase discontinuities of random values, and thus result in the instantaneous frequency swinging considerably outside the steady-state mark and space frequencies.

Of the frequency-modulation types, the shifted oscillator may be the master oscillator or a sub-multiple, or it may be a separate oscillator which is mixed with the transmitter master oscillator or its submultiple. An early keyer produced in the Bell Laboratories is noted by Vanderlippe (12) and is a unit to which the d.c. teletypewriter signal and a sub-multiple of the transmitter frequency were supplied. The submultiple frequency was shifted within the unit, and the shifted output was supplied to the trans-

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*Numbers in parentheses refer to the bibliography.

mitter where the keyer output was multiplied up to the radiated frequency and amplified. An example of the separate oscillator keyer is the Navy model FSA. In this type the direct frequency-modulation of a low frequency oscillator on a frequency of about 200 kc is produced by the action of the signaling code upon a reactance tube circuit. The output is mixed with a crystal oscillator or the transmitter oscillator and the upper sideband is selected by appropriate tuned circuits. Then follows frequency multiplication and amplification to reach the desired final frequency and power outputs. Aside from the keyer, with this system, the transmitter is generally conventional and the same equipment normally used for on-off keying is employed, often with a small reduction in power output because of the continuous duty-cycle.

With amplitude-modulation, the unwanted sideband may be removed by filtering or by outphasing. Of these two methods, the latter seems more practical. The system described in this paper illustrates the use of the outphasing technique.

2. Stability.

For any frequency-shift system a high degree of stability in the frequency-determining elements is required. One stated requirement (2) is that the frequency stability should be within plus or minus 100 cycles in a system using a value of frequency shift between 500 and 1000 cycles. Another author, Lindsay (5), states that in practice, the value of frequency shift may be allowed to change a few hundred cycles due to variations of the shift itself or the carrier frequency, or both, unless automatic frequency control or bias-correcting circuits are used. Variations in carrier frequency of a relatively slow nature, up to perhaps 2000 cycles may be tolerated, except where it is desired to keep the channel width

very small, in which total variations of plus or minus 200 cycles are desirable.

Of the various systems, the most practical way to achieve the required stability is by the use of crystal-controlled oscillators, with the oscillators in temperature-regulated compartments. With the exception of frequency-modulation of the master oscillator, the outphasing technique is alone among those listed that requires only one r.f. source, and where complete crystal-control is employed, the phasing system has the advantage of requiring only one crystal. In this system, also, it has been pointed out that the r.f. source may be at the desired output frequency with much less difficulty.

3. Flexibility.

One disadvantage for any system which uses crystal-control is the loss of flexibility in changing frequency. It was probably more for this reason than for any other single one that the type of keyer evolved possessing a separate oscillator. With the keyer oscillator frequency always the same regardless of the channel output frequency desired, the keyer circuits could be preset and optimized for this condition. That some stability was sacrificed in permitting the transmitter master oscillator to be continuously variable was considered worth the gain in flexibility. In the outphasing system it is almost mandatory for many reasons that the r.f. source be a fixed frequency, with resulting loss in flexibility. Having only one r.f. source, it is advisable for stability for it to be crystal-controlled. The matching of circuit elements including tubes is largely dependent on frequency. The r.f. phase-shift networks, which must present to the two balanced modulators components 90 degrees apart in phase are best designed for one frequency. In addition, the steps required in making the initial

balance against carrier and unwanted sideband are complex and time-consuming, encouraging again the restriction to a fixed-frequency use. It may be pointed out that there is no great need for a frequency-shift system that is continuously variable in channel frequency and the present trend is toward fixed sources, so that the above limitation is partially cancelled.

4. Linearity.

Another point of comparison is the adaptability of a frequency-shift system to the transmission of facsimile signals. Using the term facsimile in its modern interpretation as being related to transmission at high speeds using apparatus for continuous recording, the outphasing system as described here and shifting between two independent sources appear somewhat useless. No intermediate grey shades are possible because only the extreme frequencies are used. The frequency-modulation types are well suited to facsimile provided that the deviation is essentially a linear function with respect to the amplitude of the keying signal.

5. Distortion.

Discussions concerning the problem of signal transitions are taken up in the next chapter. It is shown there that the outphasing system cannot be waveshaped in the manner that frequency-modulated systems are waveshaped to reduce sideband distortion, but that techniques may be employed which reduce the distortions brought on by the inherently sudden changes in frequency. In the consideration of bandwidth in Chapter lV, it is shown that the width of the radiated spectrum can be restricted to that comparable with other systems. Since the outphasing method employs r.f. and audio oscillators which produce their base frequencies continuously, and the switch is a discrete phase shift, this system is less susceptible

to the sudden random phase discontinuities of the types employing two independent r.f. sources.

6. Simplicity.

One of the best features on a comparison basis of the system under investigation is the relative simplicity of design and circuitry leading to economy of stages and circuit components. No filters are required as in most of the other systems. Frequency conversion and frequency multiplication stages are not essential in general, for the keyer may be in itself a source of radiated energy at the channel frequency, requiring only power amplification. The feasibility of cost reduction on a multiple signaling circuit by employing one audio oscillator as the sideband source for a number of channels has been suggested to this writer. The system lends itself well to the use of miniature diodes as bridge or ring modulators for the balanced modulators, thereby being compatible with other miniaturized elements for modular packaging. Copper oxide rectifiers are suitable for operation up to frequencies of at least 4 megacycles (11), and the author's experiments have demonstrated the ability to achieve balance against the carrier of the order of 40 db with these diodes at lower frequencies.

CHAPTER III

PROBLEM OF SIGNAL TRANSITIONS

1. Nature of Transition.

One area of investigation with this system is that of the results of the mark-to-space or space-to-mark transition. In the conventional reactance tube keyer, techniques for shaping the keying waveform are used to make the signal transitions a more gradual change as the output frequency moves from one desired frequency through all intermediate frequencies to the other desired frequency. This diminishes distortion of the output frequency as well as restricting the transmission bandwidth by curtailing the higher harmonics of the keying waveform. The question arises whether waveshaping is desirable or even possible in the outphasing system, and what frequencies exist during the transition period.

Davey and Matte (2) state that

> . . . frequency-shift keying is a form of frequency-modulation in which signaling is accomplished by shifting a constant amplitude carrier between two frequencies. Frequency variations in frequency-shift telegraphy correspond to amplitude variations in amplitude modulation, thus signal transitions in frequency-shift are frequency-time transients, while in amplitude modulation (on-off keying) they are amplitude-time transients.

This is certainly true when the two frequencies are produced by a frequency-modulation process, but in the system under investigation here, each sideband is separately produced by an amplitude modulation process. In the steady state, at least, since only two frequency sources are present, no other first-order r.f. frequencies can be produced except the carrier and the fundamental sideband frequencies.

In the reactance-tube keyer, the waveform of the keying signal may be followed in amplitude point by point, each amplitude level representing a different frequency separation from the mean carrier. In the

system proposed here, however, the keying action consists of breaking a set of relay contacts and remaking contact in the opposing position, so that it is a switching action rather than a smooth amplitude or frequency transition. This also applies to the use of an electronic switch.

2. Case I.

In the ideal case, assuming no transients and zero time in the switching operation, one sideband is selected and then the other. To make this selection, the phase of the audio signal to one set of balanced modulators is instantaneously reversed, while that to the other set remains the same. Also, since the point in the audio cycle at which this switching may occur need have no common reference from time-to-time of switching, being dependent only on the particular time of change in the teletypewriter signal, we must examine first the results of such random switching. Figure 2 shows waveforms that may be taken from the keying relay, with the amplitude at the time of switching equal to zero, half-peak and peak amplitude. It is seen that in all cases except when the amplitude is zero, a discrete jump in amplitude occurs with the reversal of phase. In assuming no transients, the sudden change of amplitude may be regarded as a step function, whose frequency distribution is found by Goldman (3) to be continuous with the energy proportional to $1/w^2$, being therefore concentrated at the extremely low frequencies.

Of the waveforms in Figure 2 the case in which the signal is passing through zero amplitude is taken, since the analysis of the other cases will be similar except for the addition of appropriate phase angles and the jump in amplitude. Taking the zero time axis as the time of switching, the 180 degree phase change may be effected if we regard the signal before

SWITCHING WAVEFORMS

Zero switching time. (Case I)

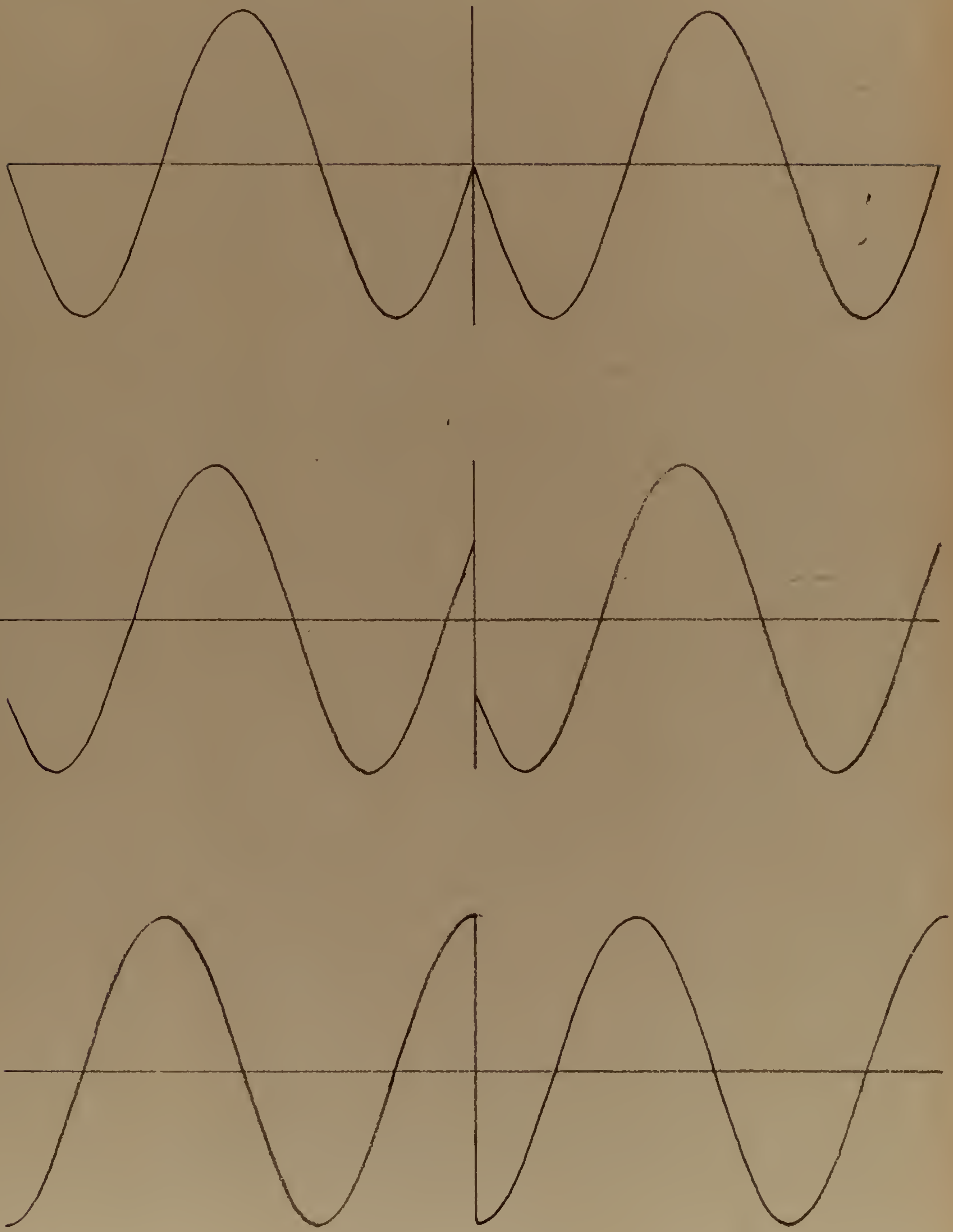


Fig. 2

time zero as being a signal of sin wt (unity amplitude for simplicity) and after time zero of -sin wt. An expansion of this waveform will have varying amplitude coefficients, depending on how many cycles before and after time zero are taken into consideration. This depends on the audio frequency and the keying interval, but the keying may be simplified to assume periodicity. Since this particular function possesses symmetry about the origin, the function is even, and the Fourier expansion can therefore be made up of a series of cosine terms alone plus a possible remaining constant. If only one cycle is considered, for example, (one-half cycle on each side of the time zero point) the expansion becomes:

$$e = -\frac{2}{\pi} + \frac{4}{3\pi}\cos 2\omega t + \frac{4}{15\pi}\cos 4\omega t + \cdots + \frac{4}{(n^2-1)\pi}\cos n\omega t, \quad (n \text{ even}).$$

This indicates the presence of even harmonics, which would represent double sideband harmonics (carrier plus and minus n times the audio frequency). A more practical number of cycles to consider is in the order of 10 cycles on each side of the origin, since an average teletypewriter signal state is about 23 milliseconds in length, where a cycle of audio frequency of 425 cycles (a common shift frequency) is just over 2.3 milliseconds in length. As was mentioned earlier, an integral number of cycles of audio frequency generally do not occur per state, but for analysis this is so taken. Taking T equal to 10 cycles or 20π radians, the Fourier expansion of the waveform becomes:

$$e = \frac{40}{99\pi}\cos \omega t + \frac{120}{91\pi}\cos 3\omega t + \frac{8}{3\pi}\cos 5\omega t + \cdots + \frac{4 \times \frac{10}{n}}{\left[\left(\frac{10}{n}\right)^2 - 1\right]\pi}\cos n\omega t, \quad (n \text{ odd}).$$

This expansion indicates the presence of odd harmonics. If a non-integral number of cycles had been taken, both even and odd harmonics would have appeared, but since for this particular instant of switching the waveform is an even function, only frequencies bearing an harmonic relation to the audio frequency are produced in this idealized condition. For switching when the audio signal has reached peak amplitude, the function becomes antisymmetrical about the origin and is thus an odd function. Its expansion would be made up of sine terms alone, but possessing only harmonics of the audio signal, since that is the source from which the wave form was derived. For other instances of switching, exact symmetry about the origin does not exist, but the wave form may still be resolved into harmonic components with the audio frequency as the basis.

3. Case II.

Considering next the condition in which no transients occur, but a finite time is taken to complete the switching process, it is assumed that whatever the instantaneous amplitude may have been at the switching instant, it suddenly drops to zero and remains at zero until the contacts close in the other position, at which time the amplitude suddenly jumps to that existing at the 1[illegible] reference signal. Here again, many wave forms may be drawn, having various relay switching times and commencing at various random points in the audio cycle. Some of the possibilities are shown on Figure 3, taking again the instants at which the audio signal is going through zero, one-half, and peak amplitude, and assuming the switching time to be of the order of one-quarter cycle.

This becomes a discontinuous function, and may again be treated as comprising five regions. These are: the presence of the audio signal in

SWITCHING WAVEFORMS

Switching time = 1/4 cycle (Case II)

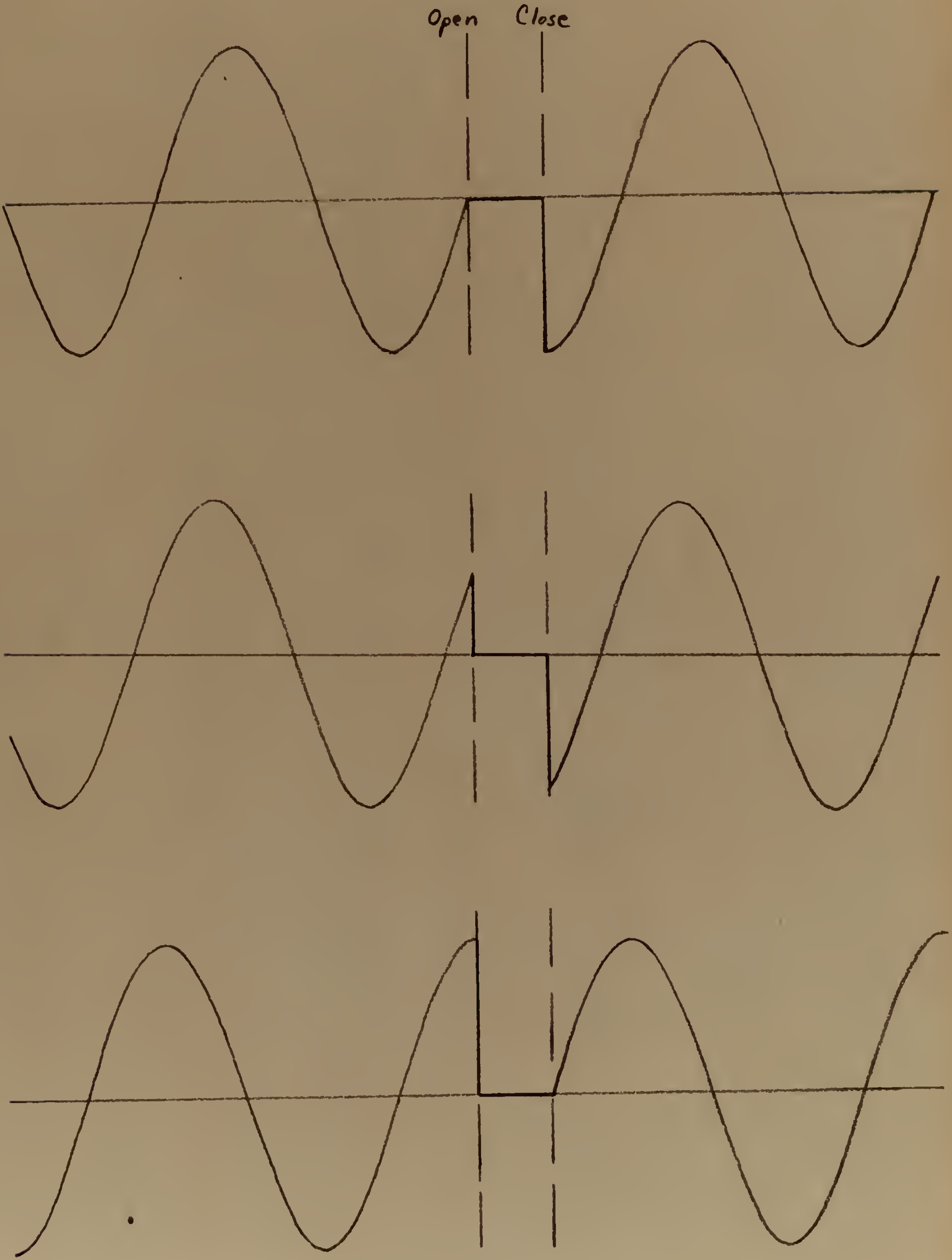


Fig. 3

zero phase reference; the sudden removal of the audio signal; the absence of the audio signal; the sudden application of the audio signal at 180 degrees relative; and the presence of the audio signal in 180 degrees reference. Of these, the first produces the lower sideband in the output, the third produces, theoretically, no output, and the last produces the upper sideband. The remaining regions are those which may be regarded again as step functions, producing a wide band of frequencies of greatest energy nearest the carrier frequency.

4. Case III.

In the final case, the presence of switching transients contributing to the wave forms are taken up. The five regions existing in the preceding case are again present, but here the sudden jumps in amplitude are replaced by exponential falls and **rises** at the switching instants. If the decay and rise times are such that they are equal to or less than the switching time, no overlap would occur, and the resulting wave forms may be such as those shown on Figure 4. Here it is assumed that it requires one-quarter of the audio cycle to switch from one set of contacts to the other, and that the rise and fall times are each equal to one-quarter cycle. Again the cases are shown for the start of switching as in the preceding figures.

As shown, marked departures from sinusoidal waveshapes occur during the transition period. During the exponential decay the waveform is of the form e^{-at}. The frequency composition of this has been derived by Fourier transforms such that:

$$F(f) = \int_0^{t_1} e^{-j\omega t} e^{-at}\, dt$$

$$= \frac{-e^{-at_1}\left(\cos \omega t_1 - j \sin \omega t_1\right) + 1}{j\omega + a}$$

SWITCHING WAVEFORMS

Switching time = 1/4 cycle ; transient = 1/4 cycle. (Case III)

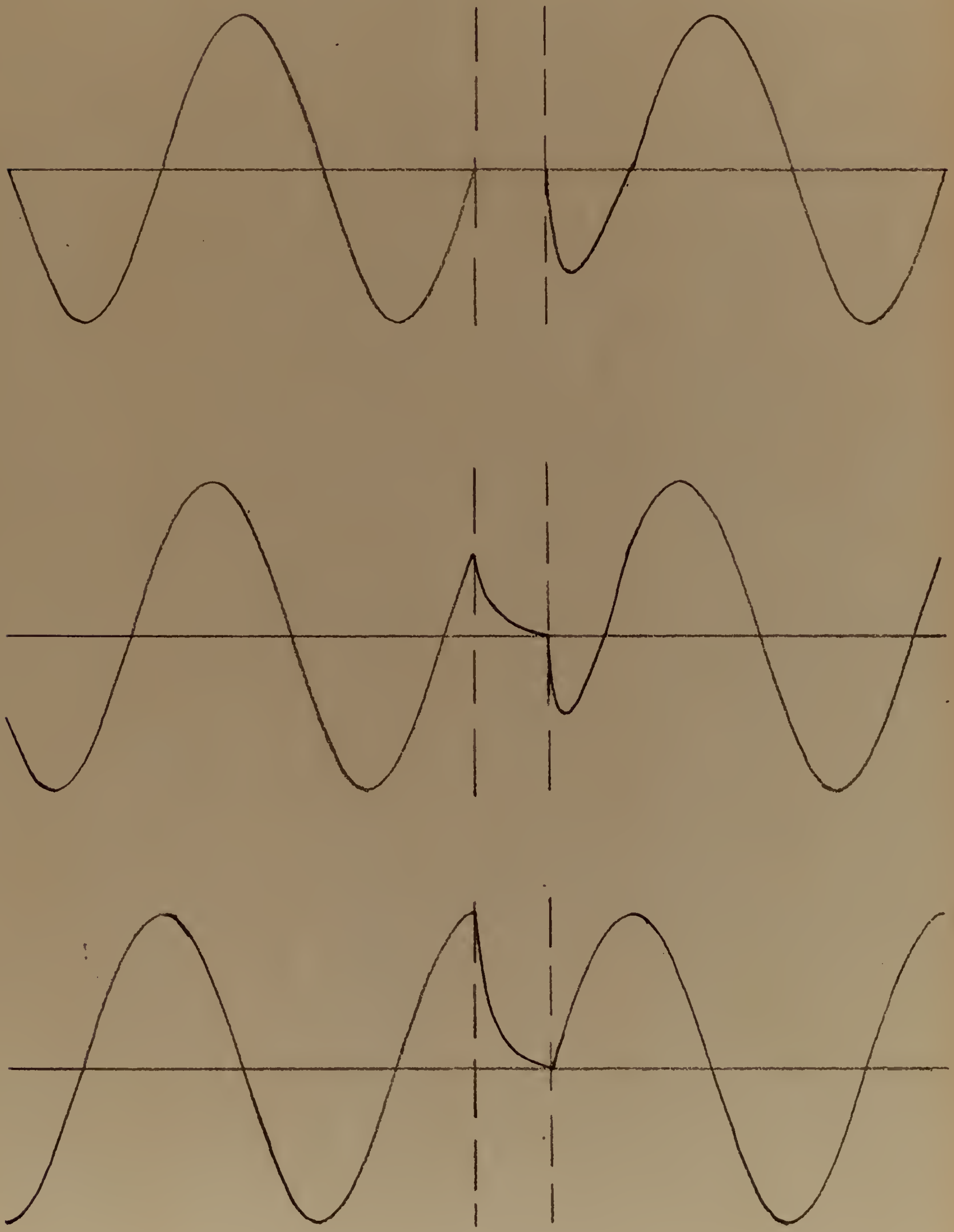


Fig. 4

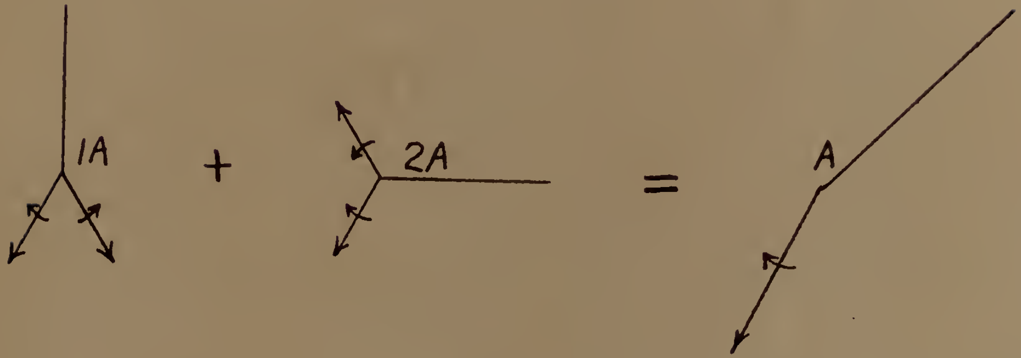
where t_1 is the interval of time under consideration. It is seen that this comprises a range of frequencies of determinable amplitude dependent on the time t_1 taken as the decay or switching time. Here again the amplitude is inversely proportional to the frequency, so that the energy distribution varies inversely as the square of the frequency and is concentrated at the extremely low frequencies. The rising transient cannot easily be resolved into frequency components, but it may be seen from the figures as being made up of a wide range of frequencies on an instantaneous frequency basis. The resultant effect on the output during the transition period would be to produce a spectrum several times the audio signal in width. In general these frequencies would be double-sideband, since the outphasing would be correct only for the designed audio frequency.

5. Uniform Phase-Shift.

It may be conceived that a great deal of the above transition frequency distortions could be avoided by making the 0 to 180 degree audio switch as a smooth phase change rather than a discrete jump. Then, as shown on Figure 5, one sideband frequency would drop rapidly to zero while the other sideband frequency would simultaneously rise to full amplitude. To perform this effect, a device or circuit would have to be provided which would furnish a rapid and accurate reversal of phase, passing through all intermediate phases, and completing its operation in a small enough time that the signal intelligence would not be changed.

VECTORIAL COMBINATIONS
SMOOTH PHASE-SHIFT

Normal combination, $\theta = 0^\circ$:



Resultant at A for other values of θ:

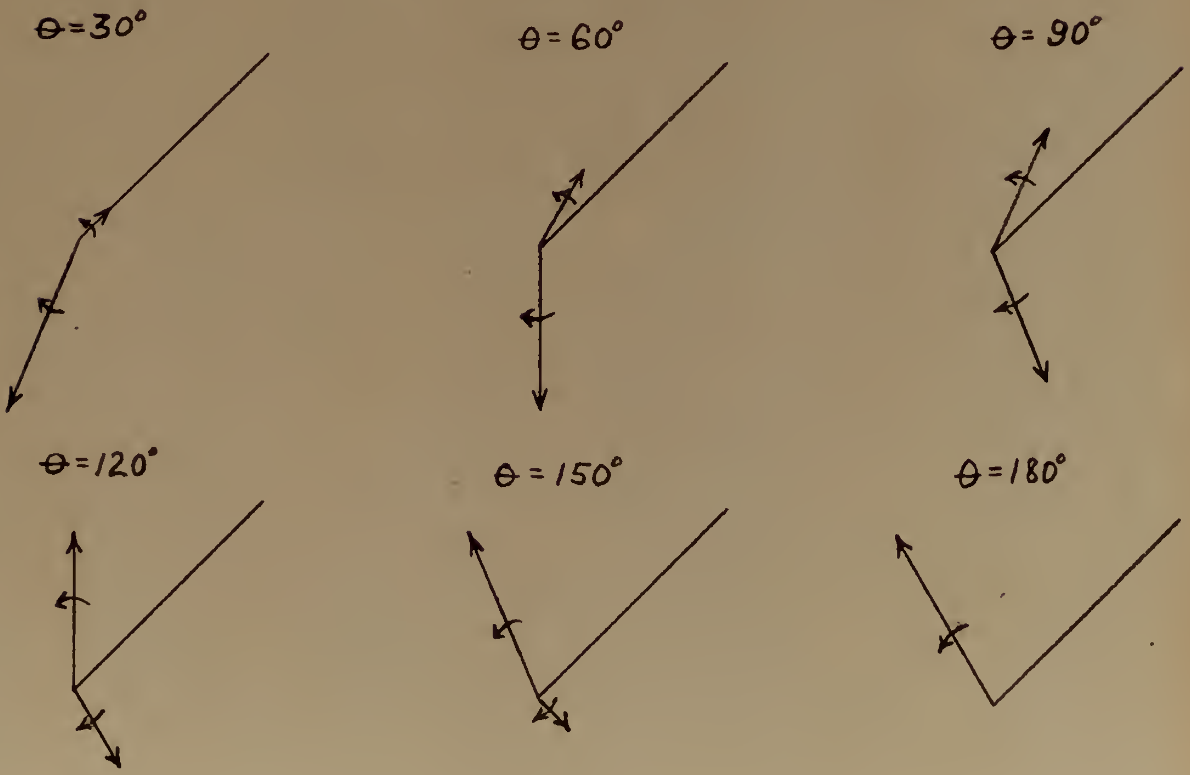

$\theta = 30^\circ$
$\theta = 60^\circ$
$\theta = 90^\circ$
$\theta = 120^\circ$
$\theta = 150^\circ$
$\theta = 180^\circ$

Fig. 5

CHAPTER IV

BANDWIDTH

1. Constant Speed Keying.

The customary technique for examining the bandwidth requirements of a system is to assume a keying waveform which is a square wave, based on constant speed keying of equal intervals of time. For the conventional keyer employing frequency-modulation, a frequency of $w/2\pi$ modulated with unbiased square wave dots of frequency $\rho/2\pi$, and of unity amplitude, Davey and Matte (2) show the following output:

$$e = \frac{2m}{\pi}\left\{ \frac{1}{m^2}\sin\left(\frac{m\pi}{2}\right)\cos\omega t + \frac{1}{m^2-1^2}\cos\left(\frac{m\pi}{2}\right)\left[\cos(\omega-\rho)t - \cos(\omega+\rho)t\right] \right.$$
$$- \frac{1}{m^2-2^2}\sin\left(\frac{m\pi}{2}\right)\left[\cos(\omega-2\rho)t + \cos(\omega+2\rho)t\right]$$
$$\left. - \frac{1}{m^2-3^2}\cos\left(\frac{m\pi}{2}\right)\left[\cos(\omega-3\rho)t - \cos(\omega+3\rho)t\right] + \cdots\right.$$

where m is the frequency shift divided by twice the signaling speed. It would not be reasonable to assume that for the outphasing system any different effect would be noted, since a selection of upper and lower sidebands in the sequence of a square wave by an outphasing method produces identically the same frequencies per state as those produced by a frequency-modulation process. For a square-wave keying waveshape the above form is also the spectrum output of the outphasing technique. If the total frequency difference between output frequencies of "mark" and "space" is 850 cycles per second, and a square wave of 23 cycles per second is employed, the resulting spectrum is shown in Figure 6.

2. Waveshaping.

That a square wave keying waveform is not specifically desired is

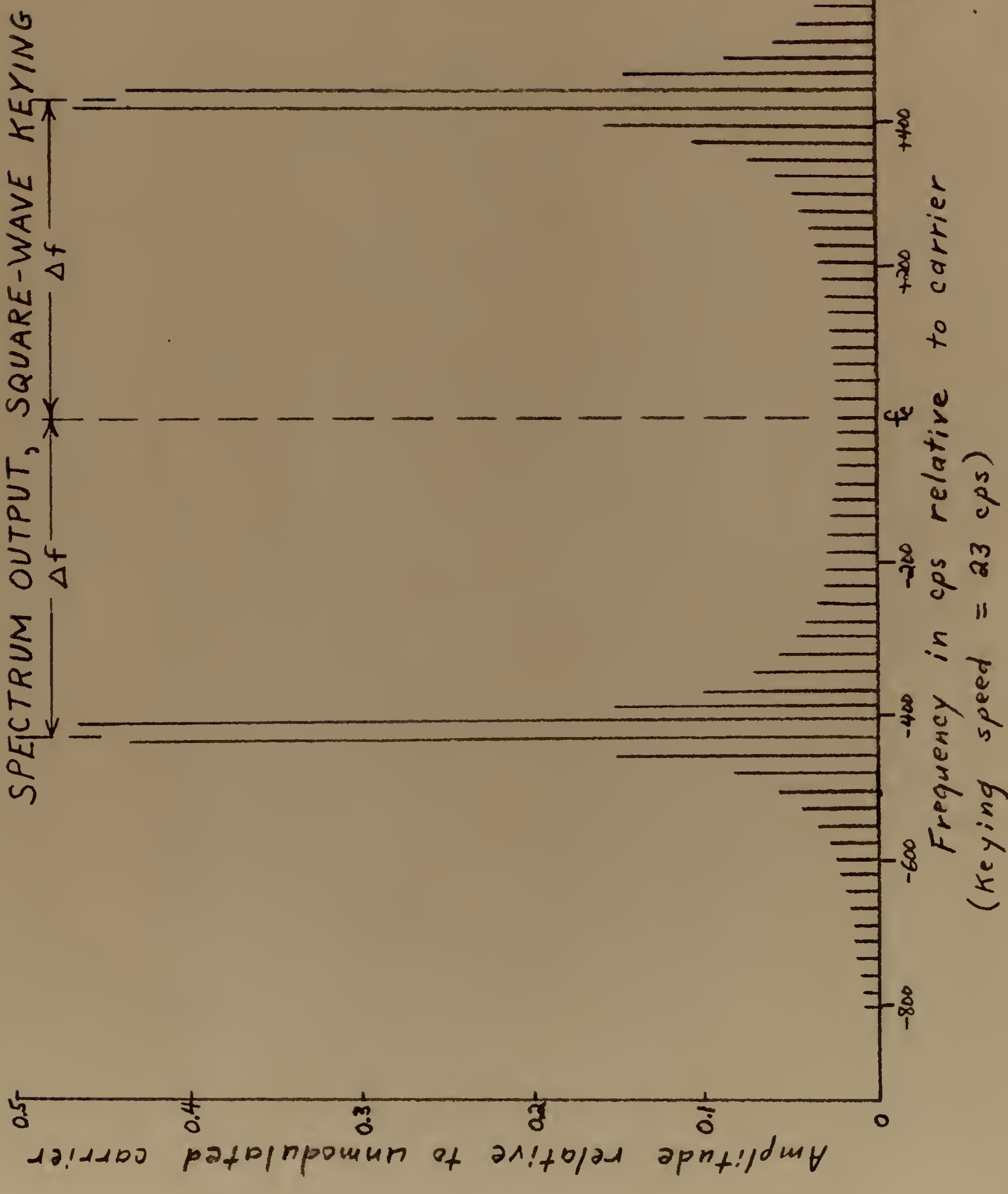

SPECTRUM OUTPUT, SQUARE-WAVE KEYING
Δf
Δf
℄
Amplitude relative to unmodulated carrier
0
0.1
0.2
0.3
0.4
0.5
-800
-600
-400
-200
+200
+400
+600
+800
Frequency in cps relative to carrier
(Keying speed = 23 cps)

Fig. 6

widely recognized. Lindsay (5) points out that keyed signal elements which are actually square waves would result in the occupation of a wide band and the creation of much undesirable and unnecessary interference. Salinger (9) further shows that a sudden change in frequency is equivalent to switching off the original frequency while the new frequency is simultaneously switched on, generating in a receiving filter two transients, the envelopes being similar and adding up to a constant value, but as the carrier frequencies are different, beats occur, affecting an FM receiver.

For the conventional type of frequency-shift keyer, waveshaping is required and possible. Shaping of the modulating wave is usually accomplished by low-pass or band-pass filters. These remove the higher harmonics of the square waveform before the waveform is applied to the frequency-shifting circuit. Considerable departure from the theoretical squarewave signal elements can be caused by attenuation of higher harmonics, provided the circuits pass harmonics up to the third of the effective modulating frequency.

Since waveshaping is desirable, the question arises here as to what extent, if any, waveshaping can be employed with the correlation system in order to restrict its transmitted bandwidth of radiated energy. To attempt to pass the keying waveform in this system through low-pass filters to remove higher harmonics and round off the waveform would only serve to distort the original intelligence by changing the time of switching an amount dependent on the sensitivity of the keying relay. If the keyer were made to switch contacts exactly at mid-amplitude, no change at all would be experienced; at sensitivities less than mid-amplitude, marking bias would be produced; at sensitivities greater than mid-amplitude, spacing bias would occur. This assumes that the positive-going portion of the wave corresponds

to "mark". Marking bias occurs when the resulting output mark signal exceeds the width of the input teletypewriter mark signal. In fact, the rising and falling switching points of the keyer are not necessarily at the same amplitude, so that other types of distortion could occur. This prevents the customary wave-shaping technique from being employed, as the output is not frequency-sensitive with amplitude.

One type of waveshaping has been mentioned earlier, wherein the change of audio phase from one extreme to the other would be made as a smooth transition rather than an abrupt shift. This is an amplitude shaping of the output, and would affect the bandwidth by removing many of the distortion transition frequencies extending between and beyond the desired frequencies. The resultant in the output would still be a transition from one sideband to the other without passing through intermediate frequencies, one sideband amplitude decreasing uniformly as the other rises.

3. Reduction of Bandwidth.

It is desired to reduce the bandwidth to the equivalent of that of on-off keying or other methods of frequency-shift keying. Sprague (10) shows that a keying speed of 23 cycles per second shaped to contain the fundamental plus a third harmonic at one-third the amplitude of the fundamental ideally produces a bandwidth of 138 cycles in an amplitude-modulation system. This is never attained in practice because of squaring of the waveform in succeeding amplifiers, so that a more practical bandwidth is about 1200 cycles. (Square-wave keying at 23 cycles per second would produce infinite harmonics, but those of greater amplitude than -40 db with respect to the fundamental extend to a bandwidth of only about 1550 cycles). For conventional frequency-shift keying, the shaped waveform

produces a bandwidth of 1100 cycles where 850 cycles mark-to-space separation exists while a square wave would produce bandwidth of about 1620 cycles. In the latter type, reduction of the total frequency shift to 250 cycles would give a bandwidth of about 430 cycles. Now for the outphasing method, using a frequency separation of 850 cycles, it would also be desirable to restrict the radiated spectrum to 1100 cycles for a dotting speed of 23 cycles per second.

One effective method of reducing the radiated spectrum that appears practical is that of highly selective r.f. circuits in the transmitter. This requires that, with the effective square-wave keying waveform necessarily employed, the outer sideband frequencies of the 24th harmonic of the dotting speed, already at a level of -28.6 db from unity amplitude (21.8 db down from the wanted sideband frequency), would have to be attenuated 11.4 db more in one or several selective circuits. The universal resonance curves show that for 11.4 db rejection,

$$Q\,\frac{2\Delta f}{f_0} = 3.3$$

so that for a bandwidth of 1100 cycles,

$$\frac{Q}{f_0} = \frac{3.3}{1100} = \frac{3}{1000}\,, \quad \text{or} \quad Q = .003\, f_0 .$$

Now, then, for a practical of 100, the mean frequency must be in the neighborhood of 33.3 kc for a single-tuned circuit. It appears that a frequency-shift keyer by this technique must have its base frequency less than, say, 50 kc, unless multiple-tuned circuits are employed to further restrict the transmitted bandwidth. Since multiple-tuned circuits may be used, this is not a serious limitation. It must be borne out that with an 11.4 db rejection to 550 cycles from mean frequency, the rejection to the

wanted sideband of 425 cycles from mean frequency becomes about 8 db, so that in the selectivity to restrict bandwidth 8 db of wanted energy is lost.

To reduce the total frequency shift would be more effective for the case where a base frequency of higher than 50 kc is desired, unless multiple-tuned circuits, with some inherent complexity of tuning, are employed. It has been shown that reduction of frequency shift narrows the band, and where the bandwidth is again desired to be within 1100 cycles, the shift would be of the order of 400 to 600 cycles total shift for 40 db rejection without reference to the selectivity of the radio circuits. Highly selective output circuits are still desired to restrict the spectrum of harmonics of the audio source and other intermediate frequencies introduced in the transition zone.

The problem of production of a wide range of frequencies associated with key clicks due to the sudden switching of the audio phase could be met in part by a rotation of phase in some manner as pointed out earlier, and also in part by the technique of selection of the switching instant at the time when the audio modulating voltage passes through or near a zero amplitude point. This could be done with considerable additional complexity of the circuitry involved, but is perhaps a very logical approach to the problem.

That the method of production of frequency-shift keying by the outphasing method in its simplest form does produce a wide spectrum output has been shown, and a few ideas toward reduction of this bandwidth have been presented. That by these techniques the bandwidth can be reduced to that comparable with other systems has also been demonstrated.

CHAPTER V

EXPERIMENTAL DESIGN

1. Description of Circuits.

An experimental model based on the block diagram of Figure 1 on page 5 was constructed in the laboratory of the United States Naval Postgraduate School. The chassis layout is presented as Figure 7. The essential features of the various circuits are explained within this chapter along with the experimental results obtained. The model was constructed merely as an engineering tool to demonstrate the techniques involved.

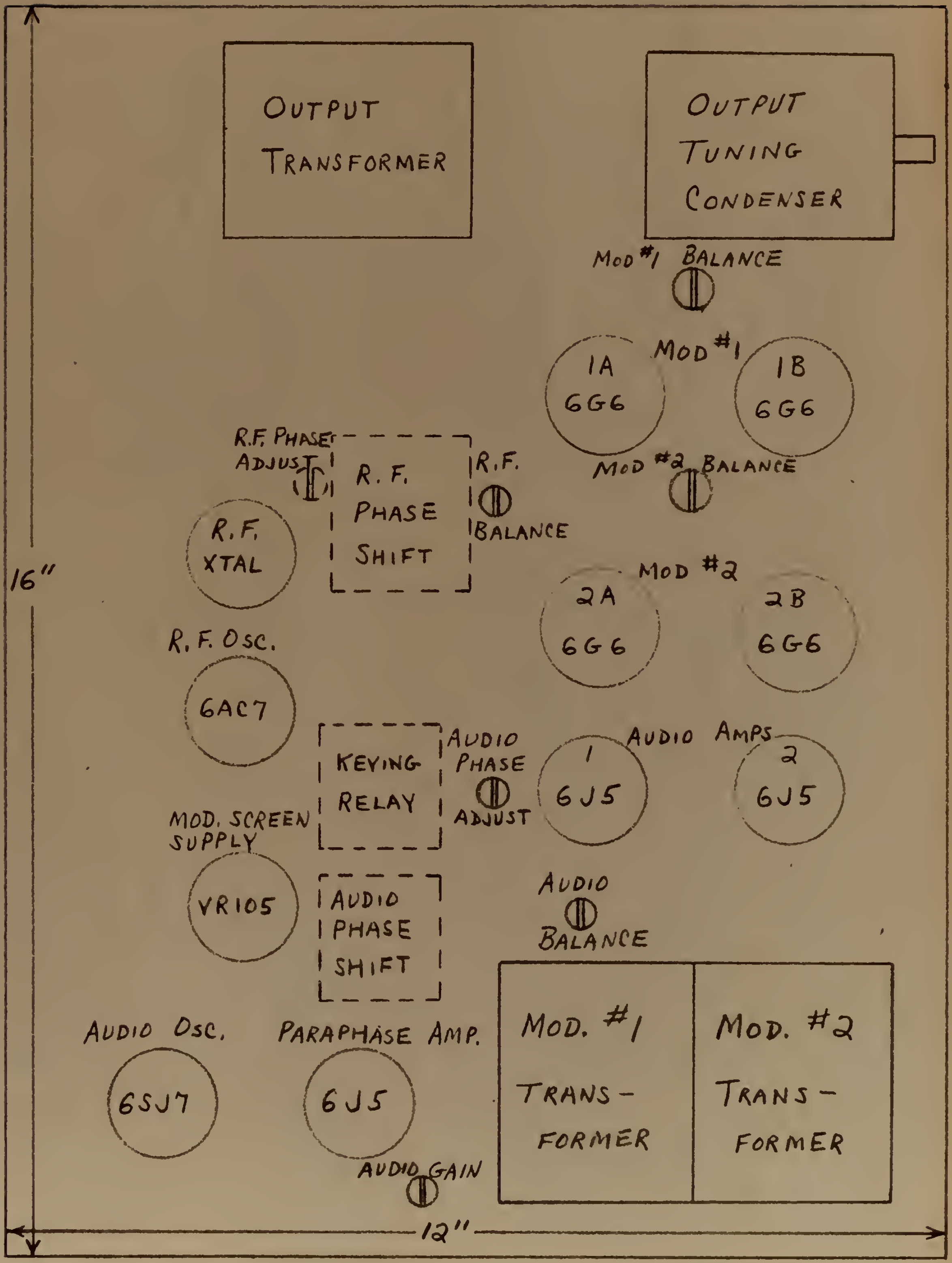
A crystal-controlled oscillator was chosen for stability, while the frequency of 3 megacycles was used to demonstrate the use of the outphasing principle at a desired channel frequency. The circuit of this oscillator is shown as Figure 8. A 6AC7 tube was used in an electron-coupled oscillator to minimize the effects of loading by the succeeding stages on the frequency-generating portion of the circuit. Only a small output was desired since the r.f. drive was to be applied to the grids of the balanced modulators.

Following the crystal oscillator is the r.f. 90 degree phase-shift network shown in Figure 9. For simplicity, each component of the r.f. signal was shifted plus and minus 45 degrees respectively to achieve the 90 degree phase difference in components presented to the balanced modulator pairs. Certain variable components were introduced for ease in adjusting the phase shift and obtaining amplitude balance. An electronic switch proved useful in checking the rough alignment of the phase-shift network with the output presented on a Tektronix 511AD oscilloscope.

The audio oscillator employed a 6SJ7 tube in an RC phase-shift feedback

CHASSIS LAYOUT

Fig. 7



R.F. CRYSTAL OSCILLATOR

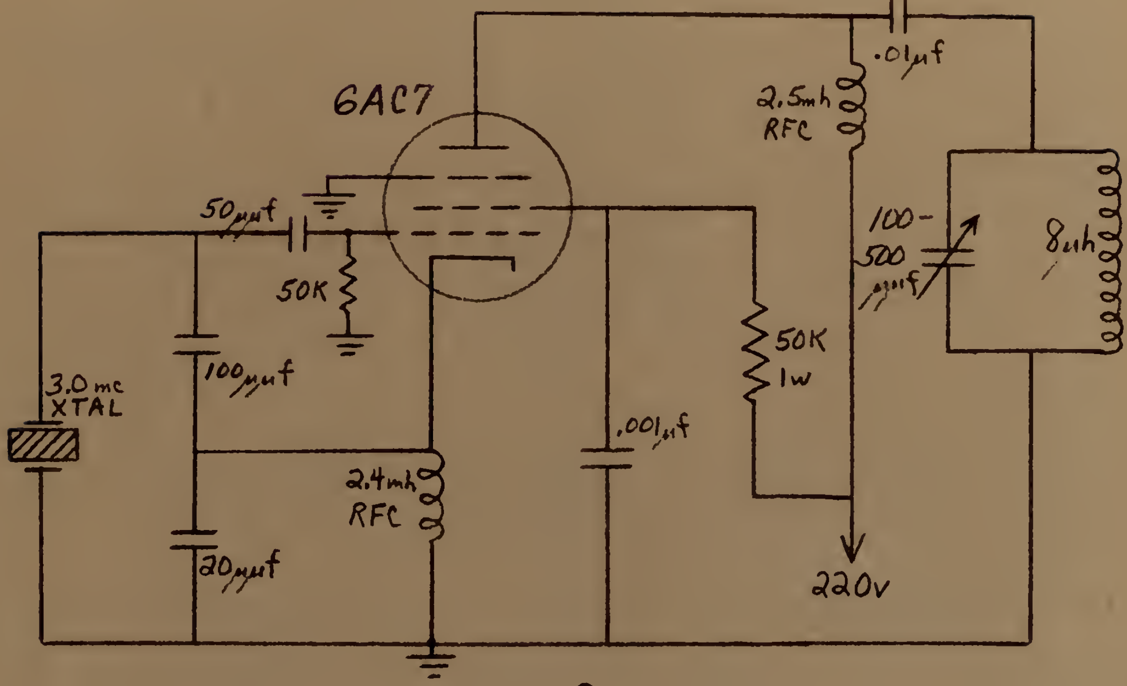


Fig. 8

R.F. 90° PHASE - SHIFT

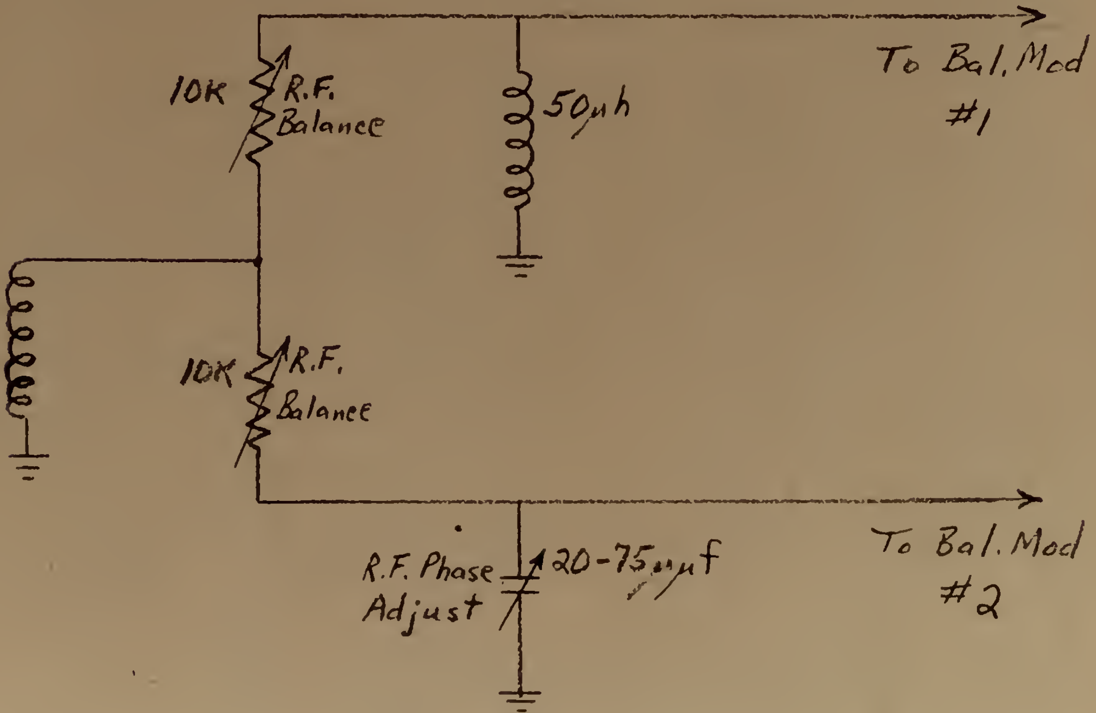


Fig. 9

network which shifts the plate output signal through 180 degrees for introduction at the grid of a signal which supports oscillations. The phase-shift network was made up of three sections, each designed to perform a shift of 60 degrees. One resistance was made variable to adjust the frequency to the desired value of 425 cycles. (With such an oscillator at a level just sufficient to maintain oscillations, an almost pure sine-wave output os obtained, while the frequency stability is very good.) The circuit employed is shown in Figure 10.

Since it was desired to have available to the keying relay two audio frequency components 180 degrees apart in phase, a paraphase amplifier was chosen (see Figure 11). This employed a 6J5 tube with equal plate and cathode resistors for the required outputs. A potentiometer was used in the input grid circuit for control of the audio gain. The gain of such a device is less than unity by virtue of cathode degeneration, but amplification was not needed at this point.

The keying relay employed was not optimum in design as a readily available relay was used. The relay had two pairs of contacts, and was so connected that the output always consisted of a signal of 0 degrees phase reference presented to amplifier number 2, while that supplied to amplifier number 1 through the succeeding 90 degree phase-shift network could be selected as 0 or 180 degrees phase reference for eventual production of the alternate sidebands. Provision was also made to break contact to both amplifiers at the switching times to prevent the generation of a double-sideband signal as described earlier. The circuit arrangement is shown in Figure 12.

The signal to be furnished to amplifier number 1 is next passed through a 90 degree phase-shift network made up of two sections, each combination of

AUDIO OSCILLATOR

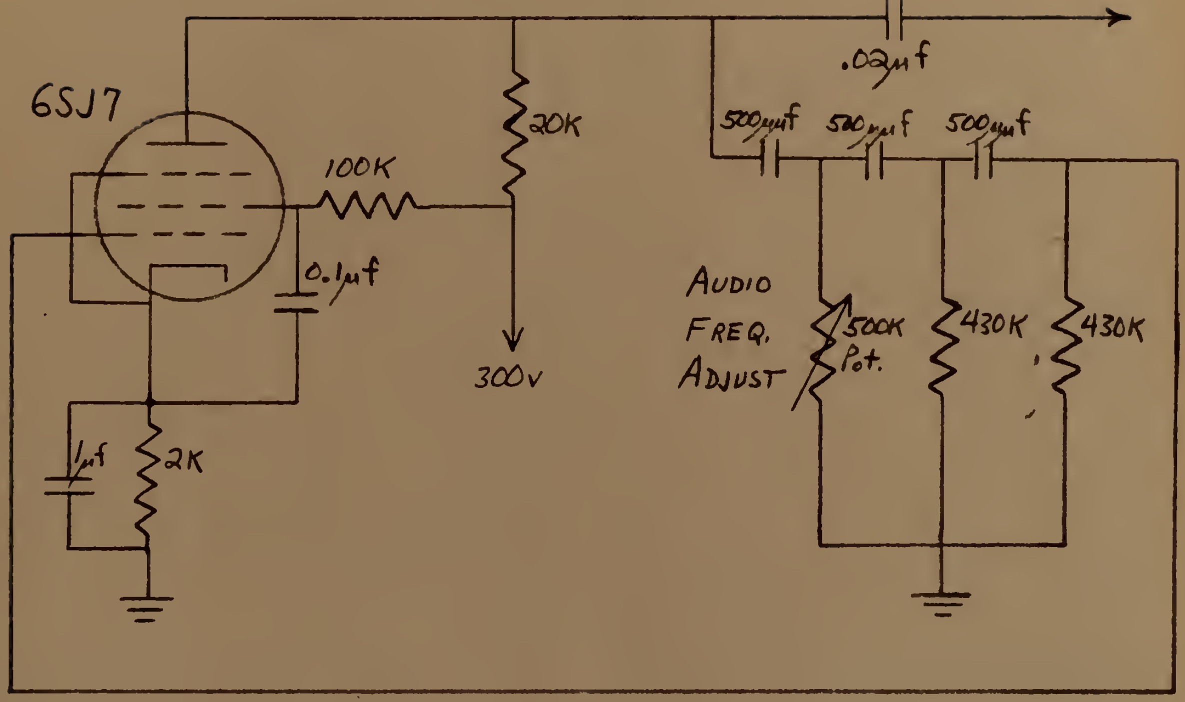


Fig. 10

PARAPHASE AMPLIFIER

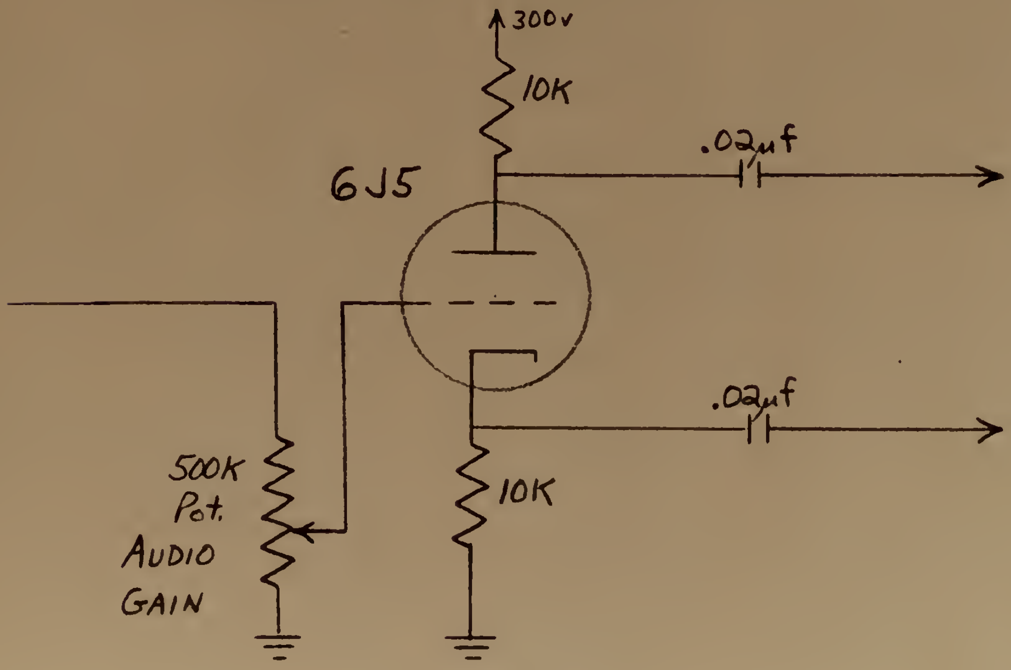


Fig. 11

KEYING RELAY

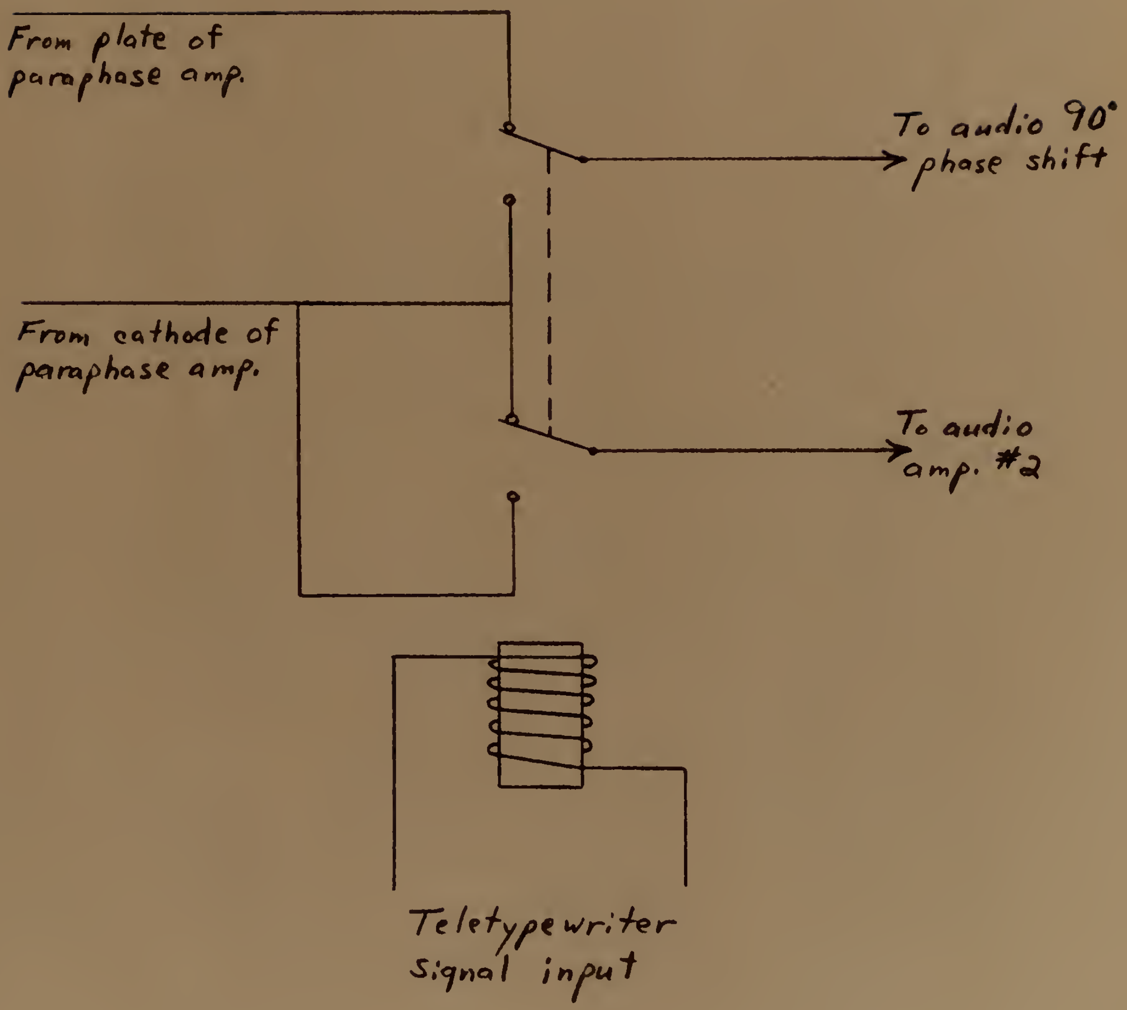

From plate of paraphase amp.
To audio 90° phase shift
From cathode of paraphase amp.
To audio amp. #2
Teletypewriter signal input

Fig. 12

R and C to provide 45 degrees shift. One resistance was made variable for adjustment of the proper phase shift, while a potentiometer was required to balance the amplitude of signal presented to amplifier number 2. Although it may have been preferable to perform the 90 degree shift as 45 degrees plus and minus, as with the r.f. components to preserve more amplitude at each point, the circuit (shown in Figure 13) was much simpler to construct.

Two reasonably identical stages of audio amplification, one for each audio component, were employed to be operated as Class A for linearity. The tubes used were 6J5's and as shown on the circuit diagrams of Figure 14, transformer outputs were taken from each plate to provide double-ended signals for push-pull modulation of the screen grids of the modulators in a balanced modulator pair. Amplifier number 2 gives outputs of 0 and 180 degrees phase reference to modulators 2A and 2B, respectively, while amplifier 1 gives outputs of 90 and 270 degrees phase reference to modulators 1A and 1B, respectively. The latter outputs are reversed by the keying selection.

The circuitry of the balanced modulators provides for application of an r.f. component to the grids of each pair of modulator tubes in parallel, while the audio components are supplied in push-pull for screen grid modulation. The double-sideband output of each modulator in a pair is placed in push-pull across an output tuned circuit where the r.f. carrier is balanced out. The combination of the outputs of both balanced modulators in the phase relationships obtained provide further for the accentuation of one sideband and the suppression of the other for each state of the keying relay. Carrier balance is obtained through the control of the relative amplitudes of r.f. signal supplied to each modulator of a pair. This is

AUDIO 90° PHASE SHIFT

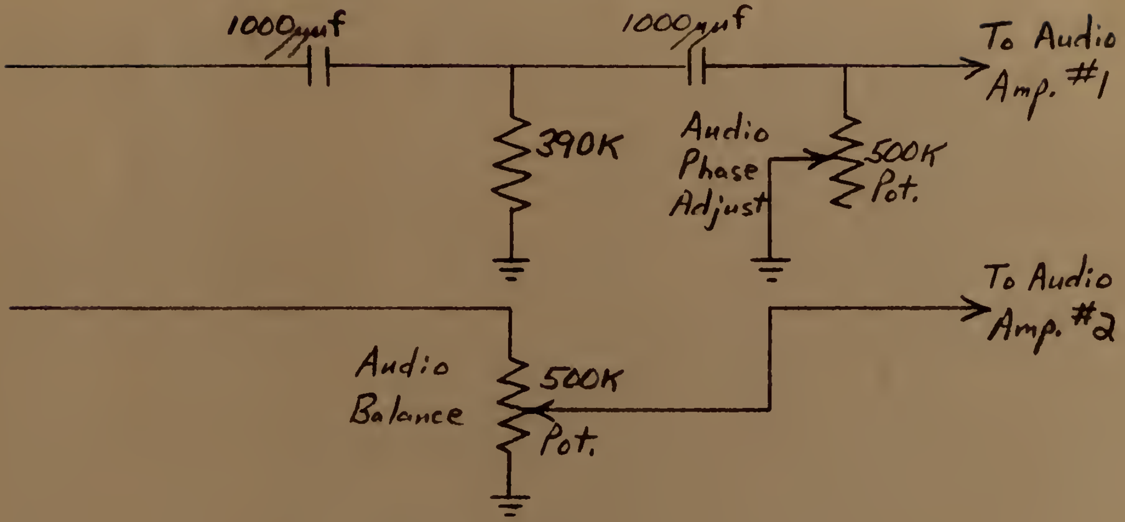


Fig. 13

AUDIO AMPLIFIERS

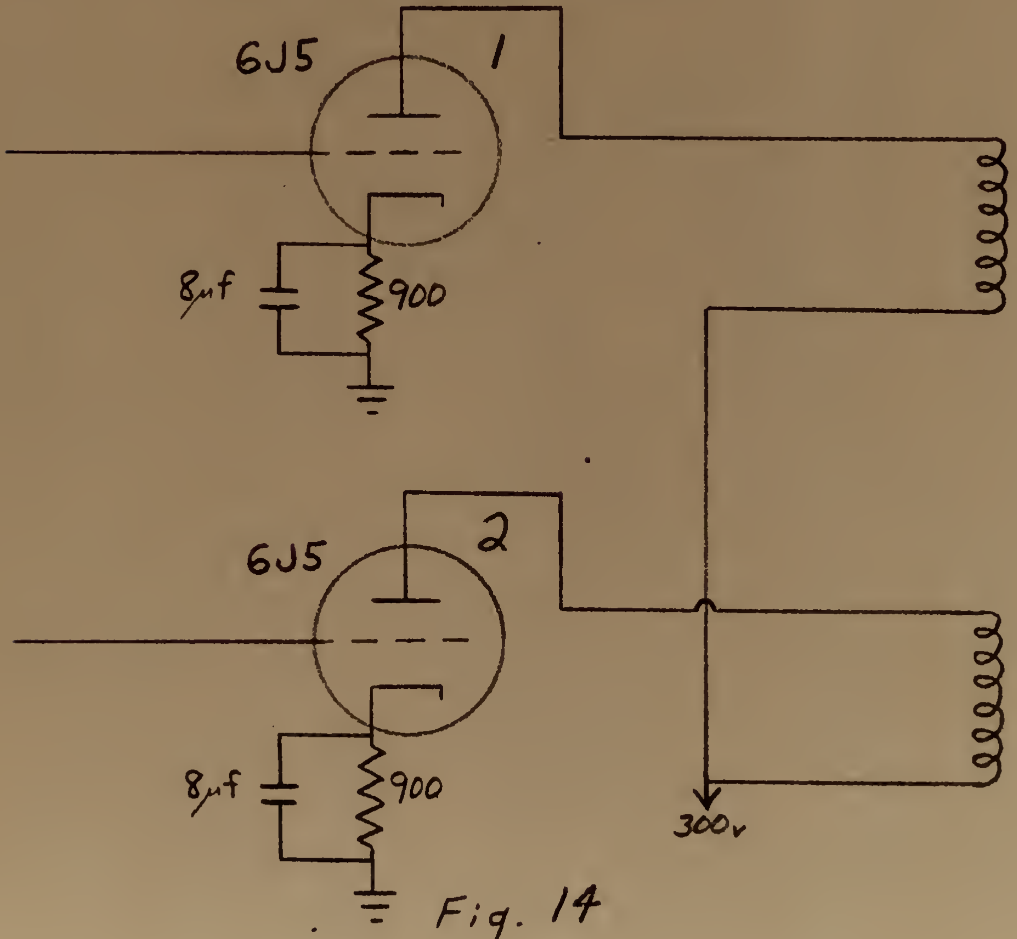


Fig. 14

done by adjustment of the potentiometers labeled "Mod. Balance", (Figure 15). Tubes were selected on a trial basis among several 6G6G tubes to obtain two pairs which could be balanced to a minimum of residual carrier within the range of the balancing controls. Different combinations of tubes seemed to have no effect on the magnitude of the balance, but only on the position of the control for the null.

Two power sources, both external to the developed model, were used to limit the load on each supply, and to provide isolation of the r.f. and audio stages. One power supply was used for the r.f. oscillator and the balanced modulator plate voltages, while the other furnished power to the audio sections, and to a voltage regulator tube for the screen voltage of the balanced modulators.

2. Alignment Procedures.

Using a stable laboratory audio oscillator at 425 cycles per second for reference, the audio frequency adjustment control was varied to provide synchronism as shown by Lissajous pattern on an oscilloscope. Next the audio gain control was set to provide the maximum undistorted signals from the paraphase amplifier. The audio phase adjust and the audio balance were varied alternately to provide equal amplitude signal components while the phase difference of 90 degrees was observed by a circular pattern on an oscilloscope. Phase differences were also observed among the four reference voltages at the output of the audio amplifiers, and corrections as necessary were made with the audio phase adjust and the audio balance to obtain the proper phase and amplitude results at these points.

Adjustment of the r.f. sections were made with the audio signals reduced to zero. The r.f. phase difference of 90 degrees between the two components was set as closely as possible at the 6G6 grid points in the

BALANCED MODULATORS

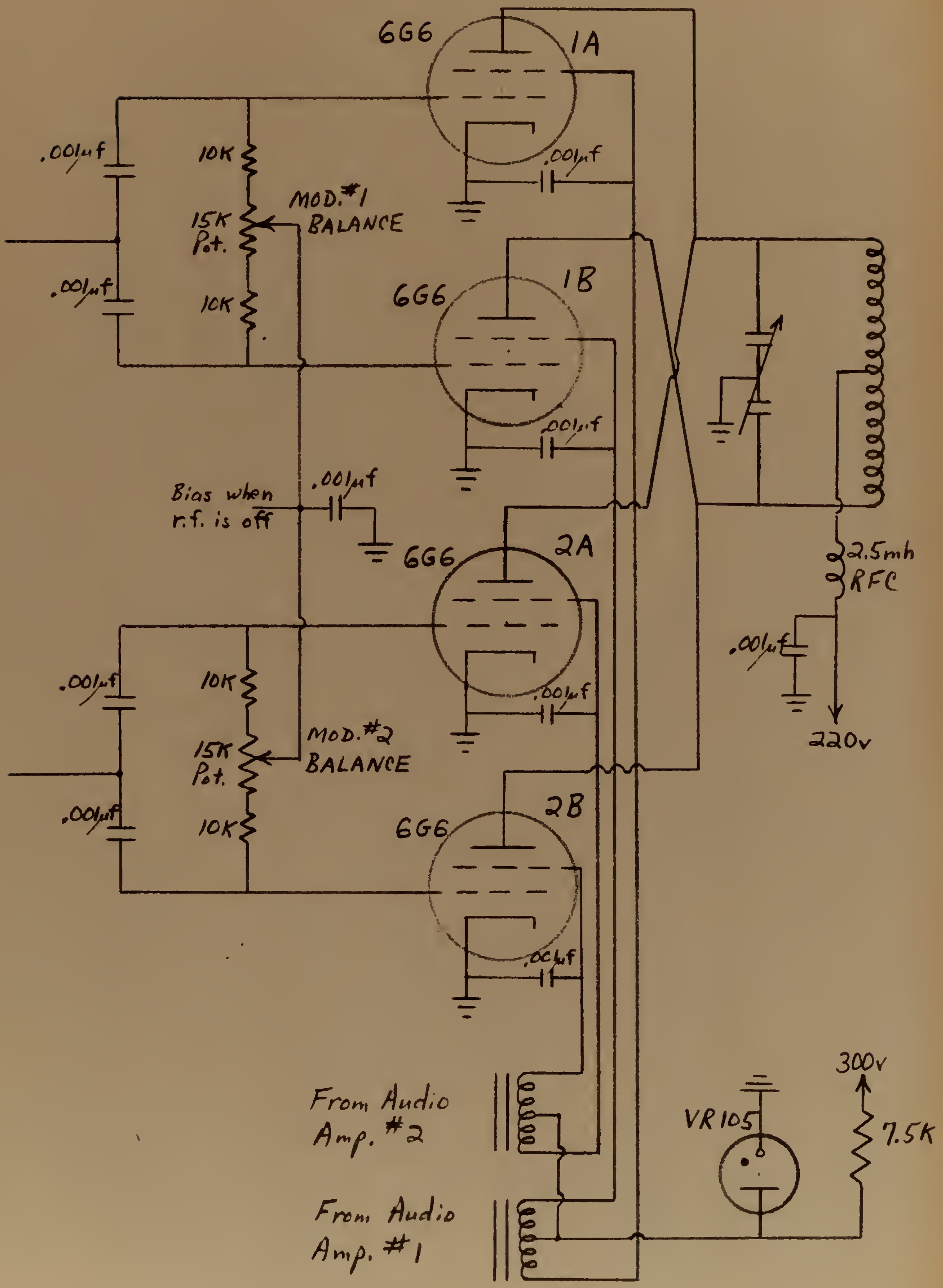


Fig. 15

manner described earlier. The r.f. balance controls were varied at the same time to provide equal amplitude signals. Taking an output from the final tuning circuit by transformer coupling to a Tektronix 511AD oscilloscope, the points of best carrier balance were observed, and necessary readjustments of the various controls were made, after the modulating signals were reapplied, for best production of essentially single-sideband output signals.

3. EXPERIMENTAL RESULTS.

Using one combination of 6G6 tubes, the average carrier balance was 29.2 db, from the following observed values:

Output Signal	Voltage (rms)
Tube 2A alone	75v
Tube 2B alone	70v
Tube 1A alone	75v
Tube 1B alone	70v
Tubes 2A and 2B	2.5v
Tubes 1A and 1B	2.4v
Tubes (all)	3.3v

The average with one tube being 72.5v and that with two tubes 2.45v, the carrier balance is $20 \log \frac{72.5}{2.45}$, or 29.2 db.

That this was not of the order of 40-60 db rejection as desired was noted, and different combinations of tubes were tried until a new result of 34.8 db was obtained. This was the best obtainable without replacement of circuit parts or repositioning of the center tap of the output coil.

With the audio modulating signals applied, the relative amplitudes of the single-sideband outputs compared with the carrier output alone was of the order of about 25 db. This, of course, depends on the degree of

modulation used, but was the best obtainable without producing audio signal distortion upon increase of audio gain.

The first attempt to measure the components of the radiated wave consisted in the use of a Navy model RBS receiver placed close to the exciter. The receiver was tuned near the mid-frequency and set on CW position. The presence of the individual sidebands was noted by the change of tone with change of keyer position. The carrier was then zero-beat, and the receiver output was introduced into a model GR 736A Wave Analyzer.

With the lower sideband being produced, the following components were observed:

425 cps . . . . 0 db (reference)
850 cps . . . . -16 db

This showed a second harmonic of the audio component down 16 db from the fundamental. Other frequencies were down at least 56 db.

With the upper sideband being produced, the readings were:

425 cps . . . . 0 db
850 cps . . . . -12 db

This is a 12 db difference in harmonics. Other frequencies were down 54 db or more.

It was quickly realized that in using the receiver, the amplifier stages would readily supply, in effect, the missing sideband as long as some carrier component were present, and that the harmonics of the audio signal may have been produced in the receiver as well as in the exciter.

The next attempt employed an LM-1 Frequency Meter. By zero-beating the principal signal for each of the three states of the keying relay, the basic frequencies were measured to be:

Lower sideband frequency 2999.75 KC
Carrier frequency 3000.15 KC
Upper sideband frequency 3000.60 KC

Next, with the Lm-1 set for a frequency slightly off the position corresponding to the carrier frequency, the audio output of the frequency meter was introduced into the GR 736A Wave Analyzer. There was no indication of the second harmonic of the audio signal being radiated as a modulation product. With the relay in the unenergized position, corresponding to lower sideband, the following were the significant readings:

90 cps . . . . 103 db (13 db down from fundamental)
335 cps 116db

With the relay in the energized position, corresponding to upper sideband, the readings were:

90 cps . . . . 103 db (12.5 db down from fundamental)
515 cps . . . . 115.5 db

Interpreting the above readings, the 90 cps measured in each case would correspond to the residual carrier component, and further indicate that the LM-1 frequency was at a point 90 cycles below the carrier frequency. The results are shown on Figure 16. It is realized that a portion of the carrier component measured was being radiated directly from the oscillator of the phase-shift networks. The frequency meter was in very close proximity to the exciter. Another element of the carrier component was that due to imperfect balance.

Another set of readings was made with the LM-1 frequency set appreciably below the lower sideband signal. The results for the two relay extremes are shown on Figure 17. Here the carrier is down 12 and 14.3

STEADY-STATE SPECTRUM A

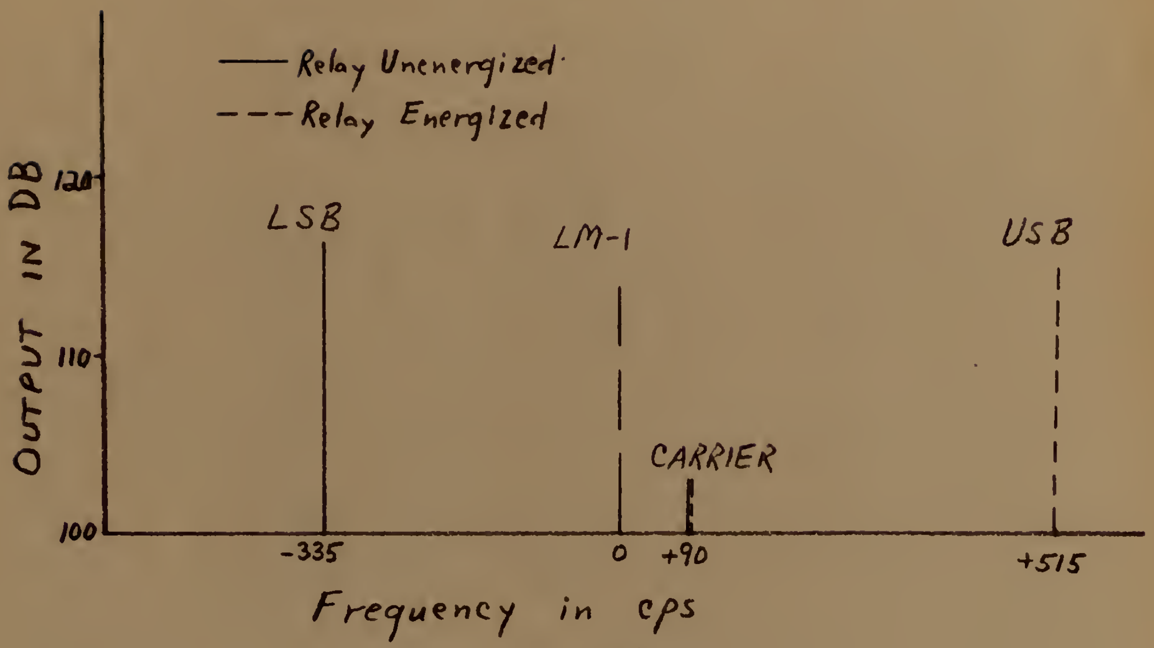


Fig. 16

STEADY-STATE SPECTRUM B

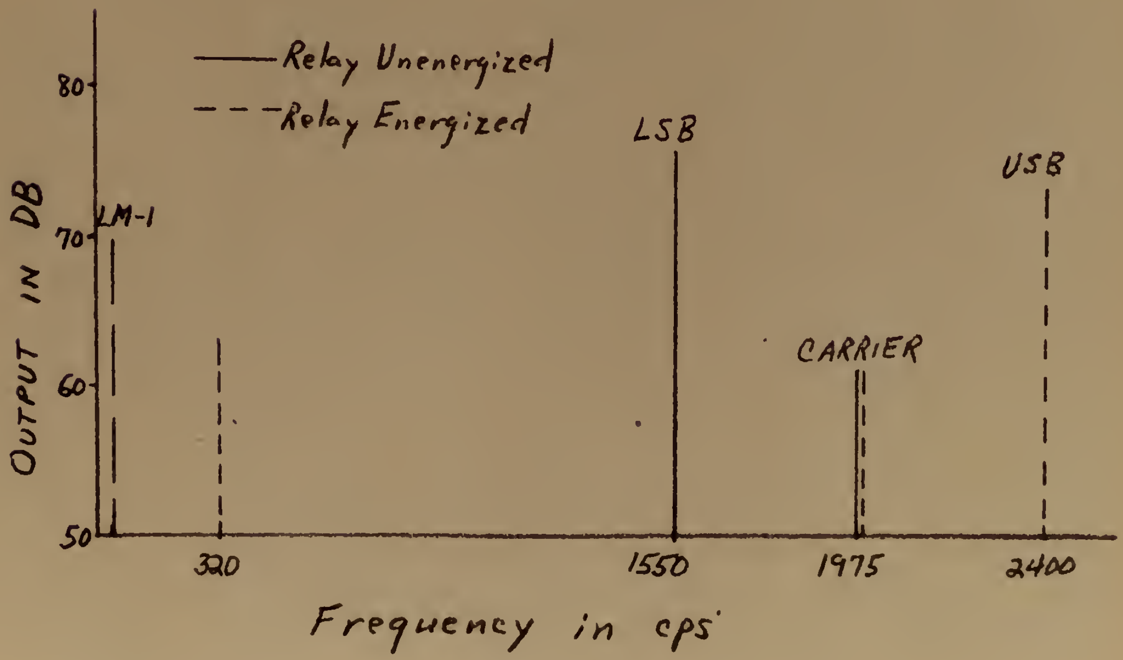


Fig. 17

db respectively from the upper and lower sidebands. An unidentifiable product frequency of 320 cps occurred on the lower side.

Random keying by tapping battery terminals of a 22.5v battery to the keying relay gave strong and objectionable key clicks, especially when removing the voltage source. That this would occur was pointed out in Chapter III. An attempt was made to observe this effect on an oscilloscope. Setting the 511AD sweep speed at a slow rate, waveforms of the general nature as that sketched in Figure 18 were observed.

4. RECOMMENDATIONS for IMPROVEMENT.

That many things could be done to improve the design is apparent, but time did not permit incorporating these changes. The r.f. oscillator should be variable in gain for better control of relative degree of modulation. Shielding should be employed around each of the r.f. radiating elements, such as the crystal, the output oscillator coil (this was employed), and the r.f. phase-shifting coil. Shielded leads should be used whenever r.f. signal are to be directed throughout the circuit. The circuit elements used in the balanced modulators should be very carefully measured in value and properly paired before installation. A wider range of tubes better suited to operate at radio frequencies could also be used.

A relay more suitable for use with teletypewriter signals should be used, or a keying tube circuit should be substituted. Some means could be adopted to minimize the production of key clicks.

A circuit should be designed to perform the 0 to 180 degree phase change of audio signal with keying in a uniform manner rather than switching. The output circuit should be more carefully balanced by proper positioning of the coil center tap and balance of the tuning capacitors.

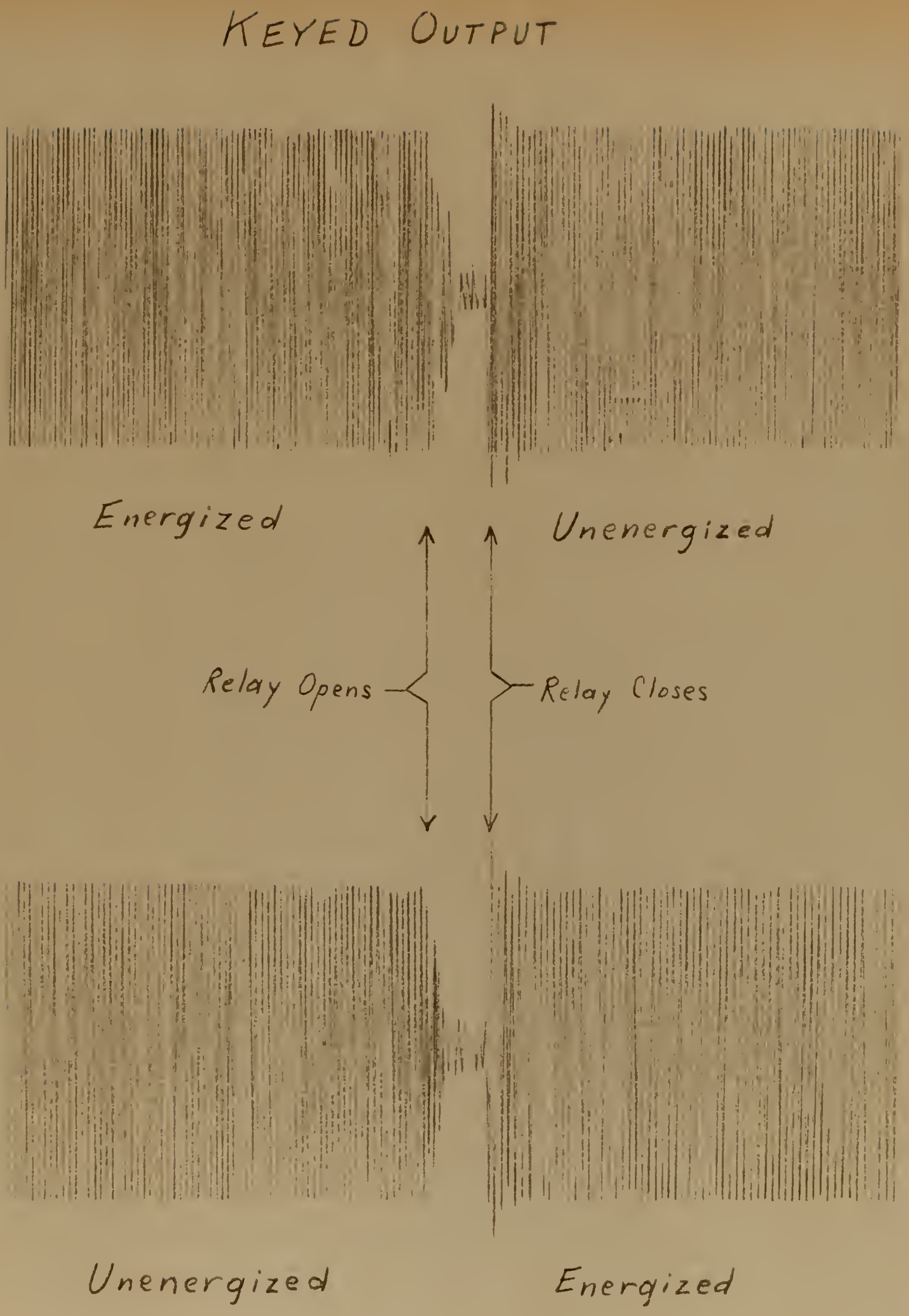

KEYED OUTPUT
Energized
Unenergized
Relay Opens
Relay Closes
Unenergized
Energized

Fig. 18

With these improvements, the testing stage could then be carried further to include constant speed keying and application of teletypewriter test messages for investigation of the radiated spectrum.

CHAPTER VI

CONCLUSIONS

Among the advantages of the outphasing method of frequency-shift keying are the relative simplicity by requiring no frequency conversion, the employment of amplitude-modulation rather than frequency-modulation, and the ability to precisely control the effective carrier shift by means of a stable audio oscillator. Although great care must be made in initial alignment and balance of the circuits, when once adjusted the system has great stability.

Frequency waveshaping is not nominally possible to restrict the radiated spectrum, although other means are available to accomplish this effect. Large amounts of distortion are caused by the signal transitions, but means have been suggested to limit these distortions.

The experimental design has shown the production of single-sideband signals capable of being alternately selected between upper and lower by outphasing. Improvements suggested in the design would show further that this system is feasible for use as a frequency-shift keyer for teletypewriter signals, and has features and performances entirely compatible with present keyers of other types.

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MAR 9 BINDERY
APR 5 RECAT
562
APR 11 BINDERY
APR 1 BINDERY
MAY 5 RECAT
DISPLAY

Thesis B885 Burrill 25281
Frequency-shift keying by the outphasing method.

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3 MAY 67 9402
20 DEC 71 16536
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